Observations of Evolving Turbulence in the Polar Solar Wind

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Abstract. The Ulysses magnetic field experiment has measured the heliospheric magnetic field in solar wind flows from the Sun's Southern polar coronal hole over a wide range of heliolatitudes and distances. We present an analysis of more than one year of data, covering a latitude range of 40° to 80°S and a distance range of 4.0 to 1.7 AU. We extend an earlier analysis of Ulysses magnetic field data and, by calculating structure functions, demonstrate that the spectrum of fluctuations in the magnetic field changed along the orbit of Ulysses within polar flows and that this change is a result of the variation in Ulysses' distance from the Sun, rather than its latitude. We interpret this change as being due to the development of turbulence in the polar solar wind.

Introduction

Between the middle of 1993 and early 1995 Ulysses spent over a year in flows from the Sun's Southern polar coronal hole, covering a large range of both heliolatitude and solar distance. The magnetic field experiment (Balogh *et al., 1992)* has produced an almost continuous set of 1 or 2 second resolution measurements of the Heliospheric Magnetic Field (HMF) in this region. Using 30 days of this data set, Horbury *et al.* (1995a) studied magnetic field fluctuations in the polar heliosphere. Using a fractal method, they identified different behaviour on different spacecraft timescales (or equivalently, HMF spatial scales). On time scales less than 1@ seconds, Horbury *et* al. (1995a) estimated the spectral index of the HMF power spectrum as being near 1.7, while at larger time scales the spectral index reduced towards 1. Ruzmaikin *et* al, (1995) studied the small state fluctuations in HMF data taken in late 1993 and early 1994 (46° - 50° S and 4.0- 3.7 AU) using structure functions and proposed an intermittent inertial range turbulence model which was consistent with their results. Smith *et al.* (1995a, b) pointed out that the low frequency fluctuations were highly Alfvénic and of large amplitude. Horbury *et* al. (1995b), using structure functions, studied 160 days of polar HMF data from late 1993 and early 1994 (44° - 69° S; 4.0- 2.9 AU): they confirmed the "breakpoint" in the spectrum at a scale of around $10^{3.5}$ seconds and that the spectral index was 1 at lower frequencies.

The shape of the HMF power spectrum in polar flows, with the spectral index near 1,7 at high frequencies but near 1 at low frequencies, is similar to that found near the ecliptic. Bavassano *et al. (1982)* found such a power spectrum in the trailing edges of high speed streams measured by the Helios spacecraft near 0.3 AU. However, the breakpoint or transition frequency was a function of solar distance: as the solar wind travelled away from the Sun near the ecliptic, the breakpoint frequency lowered. For a comprehensive review of the Helios results, see Tu and Marsch (1995). The lowering of the breakpoint frequency is at so seen out to several AU (Klein *et al.,* 1992). This is indicative of an evolution, or development, of the fluctuations. The high frequency regime, with a 1.7 spectral index, is interpreted as a turbulent "inertial range," with an energy transfer from huger to smaller scales terminated at dissipation states in the plasma. The lower frequency $1/f$ regime, on the other hand, does not seem to have transferred significant energy to smaller scales. Rather, such fluctuations may originate close to the Sun and be transported outward in the solar wind (Matthaeus and Goldstein, 1986).

The extension of the inertial range to progressively lower frequencies with solar distance may be due to the decay of the highest frequency $1/f$ fluctuations and consequent energy transfer to smaller scales. Hence, all the $1/f$ fluctuations may be unstable, but the decay rate is related to the wavelength of the waves, with higher frequency waves decaying faster. This picture is consistent with the movement of the breakpoint to a progressively lower freque ncy with solar distance.

A significant complication near the ecliptic is the presence of co-rotating stream structure. The interaction of low frequency fluctuations with stream structures such as compression regions and velocity shears is not well understood (eg. Bavassano and Bruno, 1992).

The high speed (~750 km/s) solar wind stream originating in the Sun's Southern polar coronal hole is remarkably uniform both in terms of plasma (Phillips *et al.,* 1995) and magnetic field (Balogh *et al.,* 1995) properties over a large range of latitudes. Ulysses magnetic field measurements of this region offer the chance to study HMF fluctuations unaffected by stream structure over a range of heliodistances and therefore to deduce the effect of stream structure on turbulent evolution near the ecliptic. Horbury *et al.* (1995b) suggested that polar fluctuations may have changed slightly over the distance and latitude range they studied (44" . 69° S; 4.0 - 2.9 AU), in a direction consistent with an evolution similar to that seen in high speed streams near the ecliptic. However, the breakpoint frequency was around an order of magnitude higher in frequency in polar flows compared to those near the ecliptic. Balogh *et al.* (1995) presented results from an extension of the analysis of Horbury *et al.* (1995b) in their Figure 6. Using data from 45° S to the highest heliolatitude of Ulysses at 80° S, they showed that the trend identified by Horbury *et al. (1995b)* continued to these latitudes. However, it was not possible to distinguish latitudinal and radial trends with this data set. Data from Ulysses as it travelled back towards the ecliptic at progressively smaller heliocentric distances can distinguish such trends. In this letter, we present an analysis of these data, along with a more detailed re-analysis of selected intervals of earlier polar data to give an accurate measurement of HMF fluctuations and their radial and latitudinal dependence in the polar wind near solar minimum.

Method

The calculation of structure functions in this paper is similar to that used by Horbury *et al.* (1995 b). Structure functions were first used to study the interplanetary medium by Burlaga (1991a, b) and later by Marsch and Liu (1993) and Ruzmaikin *et al.* (1995). Structure functions S are calculated for the three components of the magnetic field in the RTN coordinate system as

$$S(i,p,\tau) = \langle |B_i(t+\tau)-B_i(t)|^p \rangle \qquad (1)$$

over the data set, where i is the field component R, T or N, τ is a time lag, p is the moment of the structure function and $\langle\rangle$ denotes an average. The variation of S with τ gives information on the scaling behaviour of the data set. Specifically, if the power spectrum $P(f)$ of the fluctuations has a power law dependence on frequency,

$$P(f) \propto f^{-\alpha} \qquad (2)$$

where a is the spectral index, then similarly the structure functions will have power law dependencies on τ,

$$S(p) \propto \tau^{g(p)} \qquad (3)$$

where $g(p)$ is the scaling exponent and is a function of the moment p. The scaling exponent of the second order structure function is related to the spectral index (Monin and Yaglom, 1975):

$$\alpha = 1 + g(2). \qquad (4)$$

If the fluctuations in the data set are normally distributed, then the values of g vary linear with p,

$$g(p) = \kappa p \qquad (5)$$

where $\kappa = (\alpha - 1)/2$ from equation 4. However, it is well-established that, within the inertial range of a turbulent fluid, fluctuations are not Gaussian, both for terrestrial fluids (e.g. Anselmet *et al.*, 1984) and the solar wind (Burlaga, 1991 b; Feynman and Ruzmaikin, 1994). Within the inertial turbulent range, such deviations are often interpreted as being indicative of the intermittent or multifractal (Meneveau and Sreenivasan, 1987; Burlaga, 1991a, b; Marsch and Liu, 1993; Carbone, 1993, 1994; Ruzmaikin *et al.*, 1995; Horbury *et al.*, 1995b) nature of the turbulence which results in an increase in the spectral index from the non-intermittent value.

In this letter, we concentrate on the 2nd order structure function. For familiarity, we will quote scaling behaviour in terms of the estimated spectral index a rather than g(2): these are related by equation 4. Horbury *et al.* (1995b) calculated $S(p)$ for the R, T and N components of the HMF at time lags τ given by $\tau = 10 \cdot 2^n$ seconds, where $n = 0, 1, 2, \ldots 14$, for intervals of 327680 seconds in length. They used three time scales with which to describe their results, each incorporating three successive time lags. The small scale, from 80 to 320 s, had g(2) -0.7 and hence a - 1.7. The large scale, from 5120 to 20480 s, had g(2) -0.1, and hence a - 1.1. The medium or transition scale from 640 to 2560 s was between the other two, and had values of g(2) and α intermediate between the other two regimes. The small scale (the inertial range), also discussed by Ruzmaikin *et al.* (1995), showed significant intermittence, while the large scale did not. Direct evidence for this is provided by the non-Gaussian shape of the probability distributions of the fluctuations which have been analysed by Feynman and Ruzmaikin (1994) and Marsch and Tu (1994). We present results from the calculation of structure functions in the same manner as Horbury *et al.* (1995b) for data recorded by the Ulysses magnetic field experiment between 1993 day 300 and 1994 day 365. We also present results of a more detailed analysis of three representative intervals of data from different locations in the polar heliosphere to illustrate trends in the data. These detailed calculations, covering a wider range of scales and many more time lags, are computationally expensive and have not as yet been performed for the entire polar pass.

Sample Intervals

Calculations of second order structure functions for the normal (N) field component (other components are similar) of three intervals of polar HMF data are shown in Figure 1. Each interval is five days in duration. The starting dates for the three intervals are 1994 day 15 (3.8 AU; 50° S), 1994 day 245 (2.4 AU; 80°S) and 1994 day 345 (1.7 AU; 55°S). S(T) is plotted with two curves for each interval: higher time lags are calculated using 10 second averages of the HMF to reduce computation time, while direct 1 or 2 second samples are used for smaller time lags. The filtering effect of the 10 second averaging is apparent for lags below about 10^2 seconds, where values are significantly lower than those for the high resolution data There is a similar drop-off of values at the smallest scales measured here, for time lags under 10 seconds - this is due to data filtering,

Clearly, the three curves in Figure 1 are similar. The different amplitudes of the curves are related to the decreasing field with solar distance. There is a clear change in the gradients of the structure functions in Figure 1 (ie. the values of g(2)) at time lags of around 10^3 seconds. For time lags below this, the gradients are near 0.7, leading to values of the spectral index a near 1.7- this is the inertial range of the turbulence. Above the transition scale, values of $S(p=2,\tau)$ are fairly flat - a-1 in this region. It is this transition that is the focus of this letter.

Any changes in $S(p=2,\tau)$ over this wide range of latitudes and distances are clearly small. To examine them in more detail, we can plot a (which, from equation 4, is $1 + g(p=2,\tau)$) rather than $S(p=2,\tau)$. Figure 2 shows a as a function of τ for the same three intervals. The 10 second averaged data intervals have been extended from 5 to 20 days to improve the statistics at large time lags. The inertial range, where a - 1.7, is clear, as is the break-point when a drops towards 1. However, despite the similarities

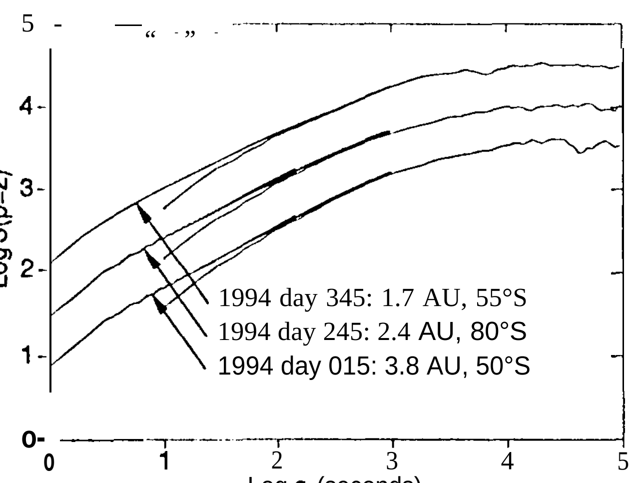

Figure 1. Second order structure functions for 3 intervals of HMF data, each 5 days in length, taken in polar solar wind flows. A change in gradient around $\tau = 10^3$ s is visible in all three intervals,

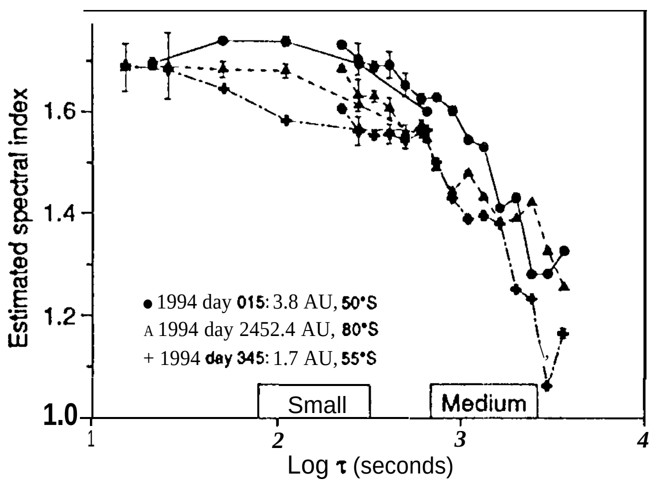

Figure 2. Estimated spectral indices derived from $S(p=2)$ for three intervals of Ulysses polar HMF data. Curves for smaller τ are calculated from 5 days of 1 or 2 second data: those for larger τ are calculated using 20 days of 10 second averaged data. Two time ranges used in Figure 3 are marked at the bottom of the Figure.

of the curves in Figure 2, significant differences are apparent. There is a consistent trend above τ ~1 minute for a to decrease (ie. the spectrum to flatten) along the orbit of Ulysses. This is true both within the lower frequency region of the inertial range and through the breakpoint. Clearly, HMF fluctuations changed along the orbit of Ulysses in polar flows.

Large Scale Trends

To establish that the changes in Figure 2 are representative of a large scale trend, the analysis of Horbury *et al.* (1995b) has been extended to include data from Ulysses after highest latitude. By sampling each latitude at two solar distances, this data can distinguish radial and latitudinal trends. The spectral index was calculated for ~4 day intervals of data taken in polar flows - data within co-rotating interaction regions or transient events were discarded - and for three time ranges, as discussed above. The small scale (80 - 320s) is within the turbulent inertial range; the large scale (5120 - 20480s) is within the $1/f$ range; and the medium state (640 - 2560s) is around the transition scale. The small and medium scales are marked in Figure 2.

Figure 3 shows the spectral indices for these three time ranges for the radial (R) component of the HMF: other components give similar results due to the large changes in field direction caused by the presence of low frequency Alfvén waves (Horbury *et al.*, 1995b). Although variations between intervals are large, *there are* distinct long term trends in the data. The spectral index of the large scale remained approximately constant over this large range of latitudes and distances. There was a small decrease in a for the small scale (in the inertial range) - this change is also visible in Figure 2. The most obvious trend, however, is in a for the transition scale, which changed from near 1.5 to near 1.2. The continuation of these trends past the highest latitude on 1994 day 256 shows that these are radial, rather than latitudinal, in nature. The relative independence of fluctuations on latitude in polar flows has proved to be a feature of the Ulysses polar HMF results.

The relatively constant solar wind speed in polar flows (Phillips *et* al., 1995) means that radial distance is approximately

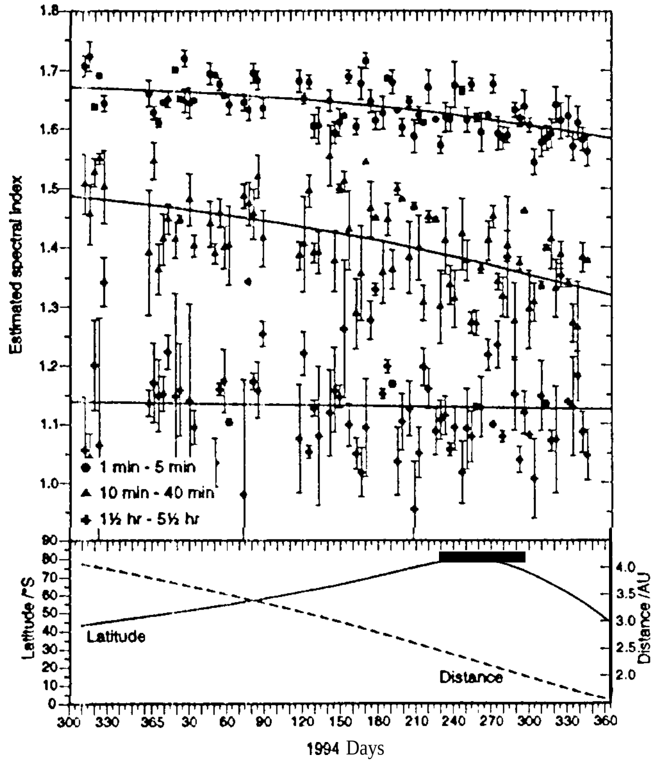

Figure 3. Spectral indices of polar HMF data calculated over three time scales over a wide range of latitude and distance in the polar heliosphere. There is a clear trend in the spectral index of the "medium" scale, within the transition of the spectrum, and a less obvious trend in the "small" scale, at the low frequency end of the inertial range. Least-squares fitted quadratic lines are shown for each of the three scales.

proportional to the time the plasma has taken to travel to Ulysses from the solar wind acceleration region near the Sun. The increase of a for the transition scale with distance (or, equivalently, with time since leaving the corona) is clear in Figure 3. This change is consistent with the evolution of the fluctuations towards fully developed turbulence and is qualitatively similar to that observed near the ecliptic (Bavassano *et* al., 1982; Marsch and Tu, 1990).

Discussion

The analysis presented in this letter demonstrates that the HMF power spectrum continues to evolve, at least out to 4 AU and probably beyond, in polar flows. The polar HMF is remarkably free of co-rotating and transient events which are pervasive near the ecliptic (Balogh *et al.*, 1995). Therefore, we conclude that inhomogeneities near the ecliptic are not the sole cause of the evolution of fluctuations: the fluctuations evolve undisturbed in polar flows. Such evolution is therefore an intrinsic property of these fluctuations. This evolution has important implications for the distant polar heliosphere. Forsyth *et al.*, "Variances of large scale fluctuations in the heliospheric magnetic field out of the ecliptic plane" and Balogh *et al.*, 'Time-scale and radial dependence of magnetic field variances in solar wind flows from the southern polar coronal hole" *(manuscripts in preparation,* 1995) have studied radial scaling of polar magnetic field fluctuations at frequencies below the breakpoint considered here. The results presented here indicate that at some point, non-dissipative scaling at low frequencies will be violated by energy transfer to higher frequencies, resulting in a steeper decline in fluctuation power with radial distance than is seen between 1 and 4 AU. It is difficult to extrapolate the behaviour up to 4 AU to the far heliosphere on the present data alone: such an extrapolation should be based on a theoretical framework of evolving turbulence.

Although polar fluctuations evolve when undisturbed by large-scale inhomogeneities, one must be careful not to neglect the influence of such structured flow on near-ecliptic fluctuations. The time scale of the breakpoint in the power spectrum of interplanetary fluctuations has been studied by several authors. Matthaeus and Goldstein (1986) found that the breakpoint was around 10 hours (ie. $\sim 10^{4.6}$ s) at 1 AU, and Klein *et al.* (1992) found that the breakpoint was near 16 hours (i.e. -1048 s) at 4 AU. These values are significantly higher (i.e. at lower frequencies) than found here in polar data, where the breakpoint is around 10^3 - 10^4 seconds. We conclude, therefore, that polar fluctuations are significantly unevolved compared to those at similar distances near the ecliptic. The primary difference between polar and near-ecliptic flows is the presence of low-speed streams, and hence interaction regions, near the ecliptic. Such inhomogeneities seem to play a role in the development of turbulence near the ecliptic, although the relationship is not entirely clear (eg. Bavassano and Bruno, 1992; Tu and Marsch, 1995). A comparison of Ulysses data taken during the recent fast latitude scan with that from the polar heliosphere may help to clarify this issue.

The long-term sampling of high-speed flows by the Ulysses spacecraft, combined with the unusually good data coverage, have enabled us to examine the scaling behaviour of the HMF extremely accurately. In particular, the results shown in Figure 2 give precise measurements of the HMF scaling and its slow changes along the Ulysses orbit. These measurements require a reexamination of theoretical models of developing turbulence. For example, although a is near the Kolmogorov value of 5/3 at high frequencies, near 4 AU a is higher than this value for $\tau \sim 100$s. This may be due to increased intermittence which can increase a, or an excess of energy in eddies near these scales. Indeed, although a detailed comparison of this data with published models of evolving turbulence (e.g. Tu *et al., 1984;* Zhou and Matthaeus, 1989; Tu and Marsch, 1990) is beyond the scope of this letter, it will be the subject of a future paper.

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